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HEATING OF A DENSE PLASMA WITH AN INTENSE RELATIVISTIC ELECTRON BEAM: INITIAL OBSERVATIONS*

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ABSTRACT

A dense ($\sim 10^{17} cm^{-3}$) plasma has been heated via the relativistic two-stream instability using a 3MeV, intense ($5X10^5 A/cm^2$) electron beam. Evidence for heating has been obtained with diamagnetic loops, thin-foil witness plates, and a 2-channel, broad-band soft x-ray detector. Measurements of energy loss from the beam using calorimetry techniques have been attempted. The measured strong dependence of heating on beam transverse temperature and the very short interaction length (<4cm) are consistant with beam-plasma coupling due to the relativistic electron-electron two-stream instability. Soft X-ray measurements made >100ns after the beam pulse are consistent with a plasma temperature < 150eV and line emission near 80-90eV.

INTRODUCTION

Two-dimensional computer simulations (1,2) predict that a cold, intense relativistic electron beam can transfer up to 50% of its kinetic energy to plasma thermal energy. The transfer takes place via the fast growing electrostatic two stream instability. Plasma heating at densities of up to $10^{20} cm^{-3}$ appears theoretically possible.

A number of experiments (2,3,4) have already produced evidence for heating via the two-stream instability at substantially lower plasma and beam densities ($n_e \lesssim 10^{13} cm^{-3}$ and $n_b \lesssim 10^{11} cm^{-3}$). Unlike previous experiments the Los Alamos experiment has been designed to optimize the beam plasma interaction at higher plasma densities (10^{17} to $10^{18} cm^{-3}$) with a beam density (n_b) of $10^{14} cm^{-3}$. At $10^{18} cm^{-3}$ with beam-plasma coupling efficiencies $\gtrsim 10\%$, the plasma energy density would be high enough to test the practicability of using hot, dense plasmas as inertial confinement fusion drivers.

The initial results from this experiment carried out at $\sim 10^{17} cm^{-3}$ have been reported elsewhere (5,6). Here, we give further details of the observations with particular attention to the energy content of the heated plasma.

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DESCRIPTION OF EXPERIMENT

Experimental Parameters. The parameters have been chosen according to guide lines established by thode (7) to optimize energy transfer to a 10^{17}-$10^{18}cm^{-3}$ plasma. From Ref. 7 the fraction of the beam's energy transferred by a cold beam is given by $\Delta W/W = 1.5S\,(1 + 1.5S)^{-5/2}$ where $S = \beta^2\gamma(n_b/2n_e)^{1/3}$ is the interaction "strength parameter." n_b and n_e are the beam and plasma electron densities while β and γ are the usual relativistic factors. $\Delta W/W$ is maximized at a value of 0.18 for $S \sim 0.45$. This maximum is based on a strictly one-dimensional analysis. Optimized transfer efficiencies for a two-dimensional ideal interaction can be expected to be higher. To achieve optimum interaction, the beam must be cold, having a transverse temperature $\sim$30 milliradians.

For this experiment the relevant parameters have been chosen to be $\gamma=7, n_b \sim 10^{14}cm^{-3}$, and $n_e \sim 10^{17}cm^{-3}$, giving S=0.56. In the future, it is expected to be able to increase n_e to near $10^{18}cm^{-3}$ and γ will be increased to ~10 in order to maintain S near its optimal value.

Beam description. The beam cross-section is a very thin annulus 2cm in diameter and 300μm thick. The peak current is ~70kA resulting in a peak current density of 0.4MA/cm^2. The pulse width is ~50ns (FWHM) while the peak kinetic energy is ~3MeV. The current waveform is roughly the shape of a 1/2 period sine wave while the voltage waveform is approximately trapazoidal. The total energy content of the beam measured at the calorimeter is ~8kJ per pulse but varies ~10% from shot-to-shot. This variation is apparently due to diode impedance collapse that occurs at varying times before the end of the voltage pulse. The beam's transverse temperature as emitted at the cathode (emission temperature) has been evaluated by using the steep variation of the beam-plasma coupling efficiency with temperature. It was found to be 20 ± 10 mrad (5,6). The diode foils are placed far enough from the cathode tip so that they have no influence on the emission process. The diode used here operates in a 9T magnetic field and has an impedance of ~37Ω (8).

Generator. The 3MV voltage pulse that energizes the diode is formed by a Marx-driven coaxial two-stage water line and fed to the diode along a magnetically self-insulated line. Power flow in the rapidly converging section (see Figure 1) is achieved with negligible loss by tailoring the inner conductor surface to be very nearly parallel to the fringing field of the magnet. Detailed descriptions of the generator, diode, and power flow are the subject of reference (6).

Targets. The experiment has been operated using both neutral and preionized hydrogen targets at fill pressures varying from 0.1 to 10 torr. The data presented here were taken at 2 torr. Preionization is accomplished by means of a Z-discharge (40 kA peak current) that takes place between the diode foil and the small graphite calorimeter (see Figure 1).

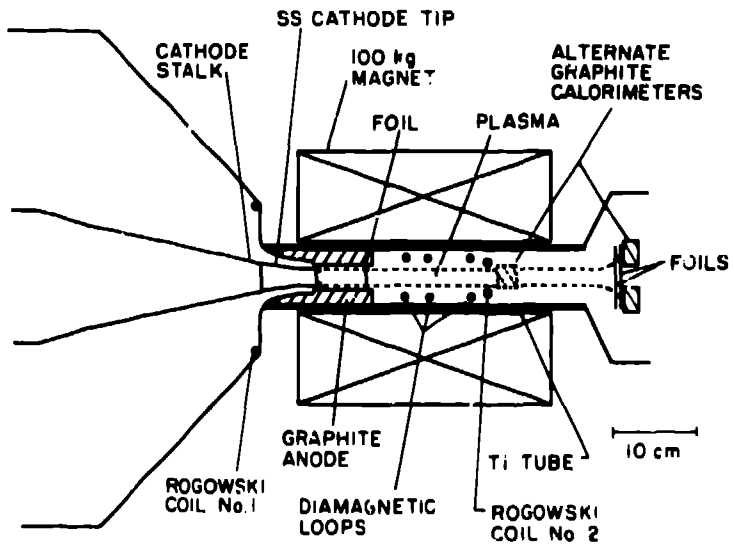

Fig. 1 Configuration of experiment.

Diagnostics. The diagnostics comprise three diamagnetic loops, two alternate graphite calorimeters (one large, one small), two thin-foil witness plates in front of the larger calorimeter, and a two-channel soft x-ray detector. The diagnostics, except for the soft x-ray detector (to be discussed below), are situated as shown schematically in Figure 1.

The three diamagnetic loops are located 4.5,7.5 and 14.5cm from the foil and are identified as loop number 1,2,and 3 respectively. Each is an electrostatically shielded one-turn coil with a radius of 2 cm. The interaction chamber wall radius is 3cm. Their sensitivity is $E_{\perp}/\ell$ 29xA Joules/m, where A is the signal amplitude in volts.
$E_{\perp}/\ell$ is the average perpendicular plasma energy content per-unit-length deposited within the loop circumference.

The graphite calorimeter placed in the fringing field of the magnet weighs ~700g. It is shielded from thermal contact with the hot plasma by two thin foils. The first foil is 25μm thick molybdenum that absorbs ~1% of the beam energy, but ~100% of the plasma energy incident upon it. The second foil (15μm Ti) shields the calorimeter against energy radiated by the first foil.

The ultra soft x-ray detector is not shown in Figure 1, but it is positioned to look at the plasma between diamagnetic loops 2 and 3.

Its construction is shown schematically in Figure 2. Each channel consists of a 0.254 mm thick NE102 scintillator shielded from stray visible light by a very thin aluminium foil. X-ray produced visible light from the scintillators is piped by pure quartz fiber optics to heavily shielded photomultiplier tubes ~2m away. The use of pure quartz fiber optics and heavy shielding of the PM tubes was necessary to reduce the interference signal generated by the electron beam gamma pulse, but despite the use of best available synthetic fused-silica fibers, it proved impossible to obtain useful x-ray data before about 100ns after the end of the beam pulse.

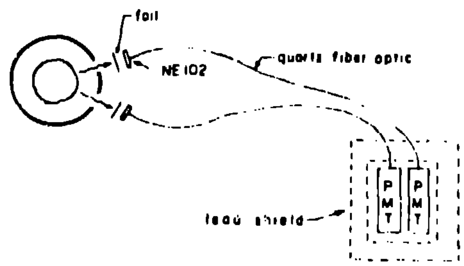

Fig. 2. Schematic of two-foil soft x-ray detector.

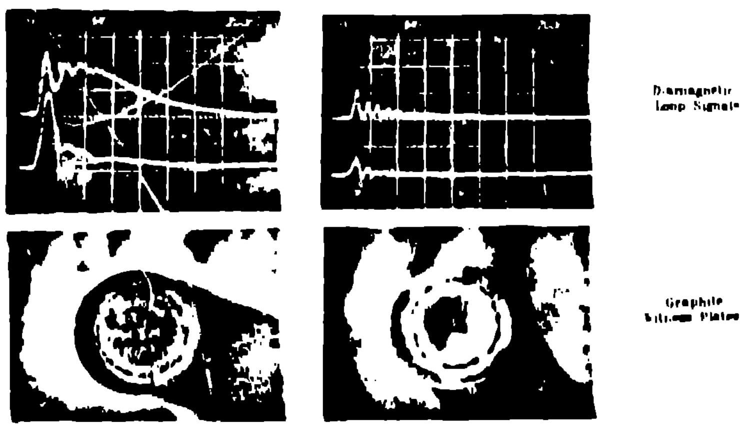

Fig. 3. Diamagnetic loop amplitudes (volts) vs. time.

OBSERVATIONS

Diamagnetic Loops. Typical scope traces of the outputs of diamagnetic loops No. 1 (upper traces) and No. 2 (lower traces) are shown in Figure 3. The traces are uncorrected for a slight integrator droop (RC=2μsec). The vertical and horizontal scales are 5V and 200ns per div. respectively. The lower panels show the corresponding damage patterns on the small calorimeter(see also Figure 1). The left panels were obtained with a cold ($\bar{\theta}_f$=22mrad) beam while the right panels were taken with a relatively warm beam ($\bar{\theta}_f$=105mrad). The divergence angles ($\bar{\theta}_f$) given here are those mean scattering angles due to scattering in the diode foil only and do not include contributions to the beam temperature from diode emission processes.The beam is on during the first $\sim$100ns. After this time the signals are not affected by the beam and represent the perpendicular component of energy deposited in the plasma by the beam. Note the sensitivity of the signal amplitudes to the beam temperature. This relationship between plasma heating and beam transverse temperature is evidence for heating via the relativistic two-stram instability discussed in detail in references (5 and 6). The damped periodic modulation on the signals is due to radial magnetoacoustic ringing. It is not present when neutral gas targets are used.

The calorimeter burn patterns show an azimuthal bunching (filamentation) of the beam observed at distances greater than a few cm from the diode foil. This bunching occurs whether or not the beam is cold (plasma heating turned on or off) and whether or not the target is preionized. As can be seen from the figure, the azimuthal mode number increases and the amplitude of the filamentation apparently decreases when the two-stream instability is operative (cold beam). The presence of the two-stream thus appears to weaken the azimuthal filamentation; perhaps by means of thickening of the beam's annular width via enhanced scattering.

Using signal amplitudes from all three loops, the total energy residing in the plasma has been measured to be $\sim$1% (80J) of the beam's total energy content. However, because of very rapid thermal conduction losses, this represents only a lower limit on the total energy transfer efficiency (5).
Witness foils. Another method of establishing a lower limit to the beam-plasma energy transfer is to evaluate the energy required to produce the observed damage to the calorimeter foils . As mentioned above, a thin (25μm) molybdenum foil shields the calorimeter from the beam heated plasma. Energy conducted axially from the hot plasma is transported by relatively low energy electrons and is absorbed within a few μm of the surface of this "witness" foil.

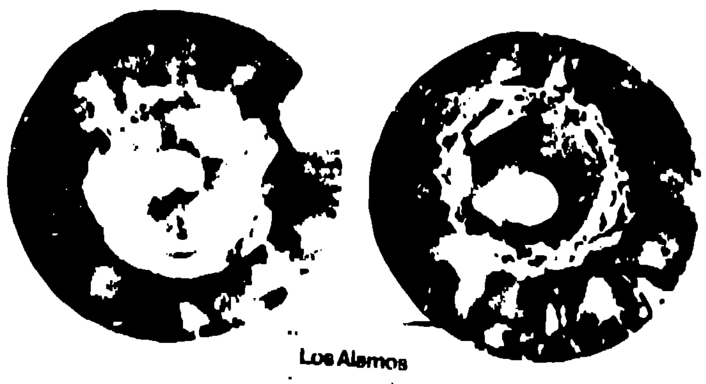

Fig. 4a.
Witness foil, hot beam.

Fig. 4b.
Witness foil, cold beam.

Figure 4 contrasts the typical damage caused to a witness foil by the beam alone (Figure 4a) with the additional damage caused by the beam-heated plasma (Figure 4b). The only difference in the two shots was the thickness of the <u>diode</u> foil (beam temperature). Figure 4a was obtained with a 30μm titanium diode foil (~100 mrad and little or no plasma heating) while Figure 4b was obtained with a 7.6μ mylar foil (~20 mrad and maximum plasma heating). The beam and plasma cross-sections are expanded by a factor of ~10 at the foil position in the fringing field of the magnet thus insuring that the foil is not melted by energy absorbed from the beam alone.

The amount of energy delivered by the beam-heated plasma to the witness foil can be conservatively estimated as follows: a) Determine the area of the foil struck by the beam. Evaluation of figure 4a gives $3.1cm^2$. b) Determine the area melted and/or ablated away. Figure 4b gives $5.5cm^2$. c) Assume that the beam-struck area is brought up to near the melting temperature by the beam and need be further supplied with only the heat of fusion to produce the observed melting. This is ~20J for $3.1cm^2$ of 25μm thick Mo. d) Finally assume that the remaining melted area was brought up from room temperature and melted by energy supplied from the hot plasma. This requires ~67J for $2.4cm^2$. Thus a minimum total energy of 87J is required from the plasma to produce the observed melting of the foil. All other energy loss mechanisms from the plasma <u>and</u> from the witness foil such as radiation, ablation, radial thermal conduction, thermal energy loss from the diode end of the heated column, heating and ionization of cold, neutral gas between the interaction region near the diode foil and the witness foil, etc. have been neglected and are significant. Thus foil melting, in agreement with the diamagnetic loop signals, indicates an absolute minimum energy coupling of ~1% .

<u>Calorimetry</u>. Because shot-to-shot reproducibility of beam energy content has limited the usefulness of simple calorimetry in determining beam-plasma coupling efficiency, self normalizing calorimetry experiments are being carried out. For these experiments only 1/2 the beam is allowed to interact with the plasma. This is accomplished by dividing the diode foil along a diameter into thick (50μm Ti) and thin (7.5μm mylar) halves. The calorimeter is also split to register the energy content of the two beam halves separately. The resulting calorimetry foil damage pattern is shown in Figure 5. The left half of the beam was cold resulting in significant foil damage from the hot plasma. The separatrix between the two halves did not noticably rotate in azimuth during propagation of the beam from the

diode foil to the calorimeter, nor was there significant mixing of the two halves. The first seven split foil shots have yielded a beam-plasma energy coupling of 7.1 ± 4.6 %.

Ultra soft x-ray detector. Using very thin (2.25μm) aluminum filters, x-ray signals from the hot plasma have been observed. It has been established that the signals are due to plasma-generated x-rays by noting that they are present only when plasma heating occurs (as shown by the diamagnetic loop signals). When a slightly thicker foil (3.0μm) is installed on one of the channels, the signal falls by a factor ~30.

Fig. 5. Split beam witness foil.

Although it is not possible to unambiguously assess the meaning of this measurement with no knowledge of the spectral shape of the emission, some qualitative conclusions can be drawn: The first is that the detector is not likely to be responding to plasma bremsstrahlung. The factor of 30 mentioned above could be explained by bremsstrahlung of low enough temperature ($T \sim 50$ eV), but at this temperature the observed absolute x-ray flux intensity is at least a factor of ten too high. A $10^{17} cm^{-3}$ hydrogen plasma even with significant impurity concentrations can not radiate enough bremstrahlung power at ~50 eV temperature to explain the observed signal amplitudes. A temperature ~ 150eV would be required. The conclusion, then, is that the detectors are responding to narrow band (line) radiation. The mass absorption coefficient of aluminum is correct ($\mu = 1.7 \times 10^4 cm^2/g$) at two energies to explain the factor of 30: 1) at 80-90eV in the L-edge absorbtion minimum; and 2) at ~400eV. However the apparent lack of bremstrahlung makes it unlikely that very much line energy is being radiated at 400eV. Thus we conclude that the scintillator x-ray detector is responding mostly to narrow-band radiation at ~ 80-90eV and that $T_{plasma} < 150$eV.

SUMMARY AND DISCUSSION

Although the results discussed here are preliminary, significant information has been gained from the experiment. As discussed in (5), experimental evidence indicates that a beam-plasma coupling via the relativistic two-stream instability has been observed. The coupling efficiency is certainly greater than 1% but could be up to 5% of the total energy content of the beam. This is to be compared to theoretical predictions ranging from 20 to 50%, but these are two-dimensional, ideal simulations where the beam parameters are constant in time. Some of the total energy content of the beam (from 25% to as much as 35%) is delivered during the rising and falling portions of the pulse where γ is low and changing rapidly in time. Although the observed coupling efficiency is lower than ideal theory would predict, it is not necessary to conclude that there is basic disagreement between predicted and observed energy transfer. In the future, characterization, scaling, and optimization of the interaction with respect to parameters such as γ, n_b/n_e, magnetic field and beam temperature, will continue to be explored and compared with theoretical models.

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